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Microwave torrefaction of rice straw and pennisetum

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HIGHLIGHTS

- Higher power levels led to higher heating value and lower H/C and O/C ratios.
- Power levels of 150 W and processing time of 10 min provided 80% energy yield.
- Energy density of biomass increased for 14% after microwave torrefaction.
- Microwave torrefaction should be very close to first-order reaction.
- Liquid and gaseous byproducts possessed 30% mass and 20% energy of raw biomass.

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ABSTRACT

Microwave torrefaction of rice straw and pennisetum was researched in this article. Higher microwave power levels contributed to higher heating rate and reaction temperature, and thus produced the torrefied biomass with higher heating value and lower H/C and O/C ratios. Kinetic parameters were determined with good coefficients of determination, so the microwave torrefaction of biomass might be very close to first-order reaction. Only 150 W microwave power levels and 10 min processing time were needed to meet about 70% mass yield and 80% energy yield for torrefied biomass. The energy density of torrefied biomass was about 14% higher than that of raw biomass. The byproducts (liquid and gas) possessed about 30% mass and 20% energy of raw biomass, and they can be seen as energy sources for heat or electricity. Microwave torrefaction of biomass could be a competitive technology to employ the least energy and to retain the most bioenergy.

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1. Introduction

In recent years, International Energy Agency (IEA) has indicated that the shortage of fossil fuels will lead to soaring petroleum price. A wide array of renewable energy technologies have been researched and developed. Biomass is a source of sustainable energy and has potential to play an important role in the future around the world. Biomass is by far the most important source of renewable energy today, accounting for about 10% of total primary energy use and 78% of total renewable energy (IEA, 2010). In most cases, agricultural waste was not properly disposed in the past. It was usually burned off in the open area to result in air pollution problems. In fact, with proper technologies, agricultural waste can be converted into green fuels and chemicals. There are many thermo-chemical conversion technologies, including carbonization, torrefaction, pyrolysis, and gasification, that have been researched and developed to treat the agricultural waste. The products of these methods can be further upgraded into various useful biofuels to generate heat and electricity.

Microwave irradiation is a kind of electromagnetic irradiation. The generation of electromagnetic irradiation is due to accelerating electric charges. Its frequency is in the range of 300 MHz and 300 GHz by general definition, and thus the corresponding wavelength is between 1 mm and 1 m. There are two mechanisms of heating by microwave irradiation. One is rotation dipoles, and the other is migration of ions. Both of them are able to heat materials quickly and uniformly. The main mechanism in this study is the rotation dipoles. Not all materials can absorb microwaves. According to the interaction with microwaves, materials can be classified into three types: insulators (transparent), conductors (reflective), and dielectrics (absorptive). Therefore, microwave heating can be regarded as dielectric heating (Jones et al., 2002). Nowadays, microwave technology has been applied for various purposes, such as chemical synthesis, digestion, drying, cooking, and so on. This can be due to the fast, uniform, and selective heating accomplished by microwave irradiation. The technology of pyrolysis induced by microwave heating has been researched to treat different

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feedstocks, including oil shale (El harfi et al., 2000), oil-palm stone (Guo and Lua, 2000), paper (Miura et al., 2001), plastic waste (Ludlow-Palafox and Chase, 2001), sewage sludge (Menendez et al., 2002; Tian et al., 2011), rock phosphate (Bilali et al., 2005), scrap tire (Appleton et al., 2005), coffee hulls (Dominguez et al., 2007), wood (Chen et al., 2008), rice straw (Huang et al., 2008), corn stalk bale (Zhao et al., 2010), oil palm biomass (Salema and Ani, 2011), and microalgae (Hu et al., 2012). These researches have shown that, by using the microwave pyrolysis, various biomass feedstocks can be converted into various products, such as bio-oil, biochar, syngas, and hydrogen, depending on operating parameters, biomass characteristics, and so forth.

Torrefaction is a mild pyrolysis process. Generally, the reaction temperature of torrefaction is in the range of 200–300 °C. Besides, the heating rate of torrefaction is usually less than 50 °C/min, because higher heating rate may lead to shorter processing time. Not long enough time would result in incomplete reaction. The purposes of biomass torrefaction possibly are to remove moisture and light organic compounds, to depolymerize long polysaccharide chains, and to produce hydrophobic torrefied biomass with high energy density and grindability. Therefore, the costs of storage and transportation can be reduced (Wang et al., 2011). Furthermore, torrefied biomass can be utilized as a solid fuel for home or industry usages. It can also be co-fired with coal in a pulverized coal-fired boiler (Bergman et al., 2005). Woody and herbaceous biomass primarily consists of three types of polymers: hemicellulose, cellulose, and lignin. Generally, hemicellulose breaks down firstly at the temperatures of 200–250 °C, then does cellulose at the temperatures of 240–350 °C, and lignin being the last component to decompose at the temperatures of 280–500 °C (Deng et al., 2009). The biomass torrefaction is mainly composed of hemicellulose pyrolysis with a partial decomposition of cellulose and lignin (Wang et al., 2011). The higher heating values (HHV's) of cellulose and lignin are nearly 18.6 and 23.3–25.6 MJ/kg, respectively (Sheng and Azevedo, 2005). The HHV of hemicellulose is close to that of cellulose due to their similar chemical structures. After torrefaction, the HHV of torrefied biomass can be increased because the contents of moisture and low HHV substances are removed or decomposed.

This article is about the research of microwave torrefaction of two biomass feedstocks, rice straw and pennisetum. The primary aim is to study the operation setting, product analysis, energy assessment, reaction kinetics, and applications of microwave torrefaction.

2. Methods

2.1. Materials

The feedstocks were rice straw and pennisetum provided by Industrial Technology Research Institute (ITRI), Taiwan. They were stored at room temperature for about one year and had nearly the same moisture (about 5 wt.%). The feedstocks were shredded and then sieved by 50 mesh (0.297 mm) screens. Before torrefaction experiment, the quartz crucible was filled with the biomass until its volume was about 80% occupied. This means that about 7.61 g rice straw or about 7.06 g pennisetum was used per batch due to their different densities. Ultimate analyses of the feedstocks were done by elemental analyzer (Perkin–Elmer 2400; Heraeus varioIII-NCH). Proximate analyses were carried out according to Standard Test Method D5142. Lignocellulosic analyses were in accordance with methods provided by school of Forestry and Resource Conservation, National Taiwan University.

The general compositions of rice straw and pennisetum are shown in Table 1. It can be seen that the two biomass feedstocks should have similar organic components. Their polysaccharides contents (hemicellulose and cellulose) were very close. The major differences lay between their lignin and chemically stable contents. The lignin content of pennisetum was about 9.3 wt.% higher than that of rice straw, while chemically stable content (ash and others) of pennisetum was about 9.7 wt.% lower than that of rice straw. Besides, both combustible content (volatiles and fixed carbon) and HHV of pennisetum were a bit higher than those of rice straw.

Table 1
General compositions of rice straw and pennisetum.

	Rice straw	Pennisetum
Moisture (wt.%)	5.46	5.20
Proximate analysis (wt.%) [a]		
Volatiles	88.78	93.34
Fixed carbon [b]	1.43	0.67
Ash	9.82	5.99
Lignocellulosic analysis (wt.%) [a]		
Hemicellulose	19.50	22.70
Cellulose	42.32	38.49
Lignin	25.79	35.10
Alcohol–benzene solubility	1.62	2.65
Ash and others [b]	10.77	1.06
Ultimate analysis (wt.%) [c]		
C	46.24	46.53
H	6.21	6.36
N	1.32	0.25
O [b]	46.23	46.87
Higher heating value (MJ/kg) [a]	16.16	16.98

[a] Dry basis.
[b] Calculated by difference.
[c] Dry ash free basis.

2.2. Experimental device and procedure

This study used a single-mode (focused) microwave device with 2.45 GHz frequency. The schematic diagram of overall microwave torrefaction set-up can be found elsewhere (Wang et al., 2012). The shredded and sieved biomass feedstock was filled in a quartz crucible. Then it was placed inside a quartz tube and precisely in the pathway of microwaves. In order to maintain anoxic circumstances, Nitrogen gas was purged into the system with a flow rate of 50 mL/min. After purging for about 30 min, a power supply was turned on and switched to the designated microwave power levels for the designated processing time. Reflection microwave power levels were controlled to be less than 10% incident ones during the whole experiment period. After reaching the designate processing time, the power supply was turned off and the carrier gas was shut down, and then the tar and gas collectors were removed and sealed. After the torrefied biomass was self-cooled down to close to 100 °C, it was removed and placed in a desiccator for few hours.

2.3. Product analysis

The proximate analysis was in accordance with American Society for Testing and Materials (ASTM) standard test method D5142. Elemental analysis was carried out by Perkin–Elmer 2400 Elemental Analyzer. The heating values of raw and torrefied biomass were determined by CAL2K ECO calorimeter. The analysis of gaseous product was executed by Perkin–Elmer Auto System XL gas chromatography–thermal conductivity detector (GC–TCD). The temperatures of injector, oven, and detector were 100, 90, and 150 °C, respectively. The flow rate of carrier gas was 15 mL/min without split. The liquid product was analyzed by Perkin–Elmer Turbo Mass Gold gas chromatography/mass spectrometry (GC/MS). The initial temperature of oven was 45 °C held for 3 min, followed with a program from 45 to 300 °C by the rate of 5 °C/min, and then held for

5 min. The flow rate of carrier gas was 1.5 mL/min with a split of 20 mL/min.

3. Results and discussion

3.1. Temperature profile

Reaction temperature is one of the most important factors affecting thermal treatments. Fig. 1 is the temperature profiles of microwave torrefaction of rice straw and pennisetum at the microwave power levels of 150, 200, 250, 300, and 350 W. It shows that higher microwave power level contributed to higher heating rate and final temperature, and this was applicable to both rice straw and pennisetum. When the microwave power level increased from 150 to 350 W, the final temperature and average heating rate in the first 10 min both increased from 237 to 423 °C and from 12.9 to 31.2 °C/min for rice straw. Similarly, the final temperature and average heating rate in the first 10 min both increased from 252 to 394 °C and from 14.8 to 29.2 °C/min for pennisetum. These temperature profiles were analogous to a logarithmic curve, and thus the temperature increased much slowly after about 10–15 min processing time.

Generally, the final temperature and heating rate of rice straw were both higher than those of pennisetum. Therefore, this may imply that rice straw can absorb more microwave irradiation than pennisetum, which means rice straw has better dielectric property than pennisetum. Besides, unlike the final temperature of pennisetum to stably increase 25–40 °C every increment of 50 W, the final temperature of rice straw increased 70, 62, and 16 °C when microwave power levels were raised from 150 to 200 W, from 200 to 250 W, and from 250 to 300 W, respectively. It is thus reasonable that rice straw is more sensitive to the microwave power level than pennisetum, and the power levels of 200–250 W provide better heating efficiency for rice straw.

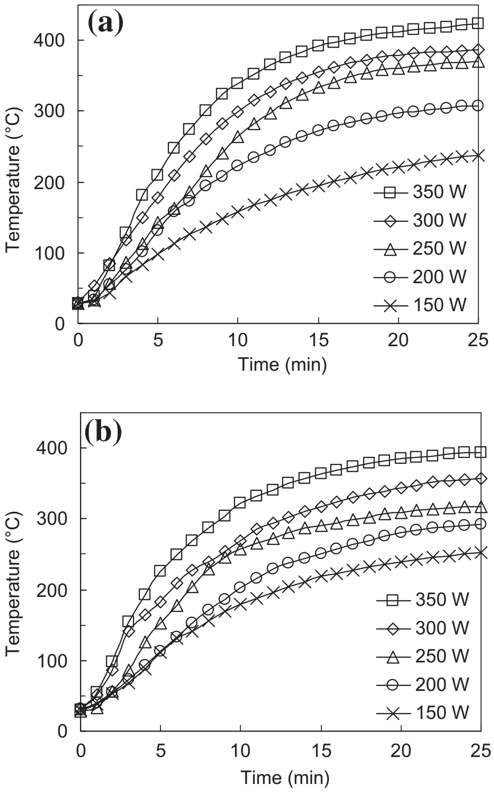

Fig. 1. Temperature profiles at different microwave power levels. (a) Rice straw; (b) pennisetum.

3.2. Composition of torrefied biomass

The proximate and ultimate analyses of torrefied rice straw and pennisetum are shown in Table 2. With increasing microwave power levels, volatiles content decreased while fixed carbon and ash contents increased. The decomposed volatiles may include part or all of the extractives, hemicellulose, and cellulose contents, depending on the reaction temperature due to microwave power levels. Figs. S1 and S2 (see Supplementary data in the online version of this article) show the thermogravimetric analyses (TGA) of raw and torrefied rice straw and pennisetum, respectively. The TGA curve of torrefied biomass was more different from that of raw biomass at higher microwave power level. At the microwave power levels of 250–350 W, it can be seen that there is no s-shaped curve at about 200–400 °C, which exists in the curve of raw biomass. This could be regarded as evidence that nearly all of the hemicellulose and cellulose were decomposed or vaporized by microwave torrefaction at higher power levels. Therefore, the difference between the TGA curves of raw and torrefied biomass could provide the information of decomposed volatiles such as weight loss and timing. Besides, the quantitative analyses of lignocellulosic contents can be approximately determined by using the TGA results. Yang et al. (2007) indicated that among the three major components of biomass, lignin was the most difficult one to decompose and its decomposition happened slowly under the whole temperature range from ambient to 900 °C. Therefore, a small part of lignin content should be reacted as well during the microwave torrefaction.

Ultimate analysis of torrefied biomass showed that C content increased but H and O contents decreased when the microwave power levels increased. Thus, both H/C and O/C ratios decreased with increasing microwave power levels. The atomic H/C and O/C ratios of as-received rice straw were 1.61 and 0.75, and those of as-received pennisetum were 1.64 and 0.76, respectively. After torrefaction at 350 W microwave power levels for 25 min processing time, the atomic H/C and O/C ratios of torrefied rice straw were 0.44 and 0.15, and those of torrefied pennisetum were 0.46 and 0.14, respectively. Compared with the raw biomass feedstocks, these ratios were much closer to those of coal and charcoal. Besides, less H/C and O/C ratios may contribute to less smoke and water–vapor formation and reduced energy loss during combustion and gasification processes (Tumuluru et al., 2011). Compared with torrefied rice husk and sugarcane bagasse (Wang et al. 2012), the H/C and O/C ratios of torrefied rice straw and pennisetum were generally close to those of sugarcane bagasse but less than those of rice husk. Therefore, it seems to be more difficult to generate torrefied rice husk with low H/C and O/C ratios.

3.3. Heating value of torrefied biomass

For being seen as an alternative fuel or energy source, the heating value of biomass after microwave torrefaction is undoubtedly important. Fig. 2 shows HHV's of torrefied biomass at different microwave power levels for 25 min processing time. The average HHV's of as received rice straw and pennisetum were 16.16 and 16.98 MJ/kg, respectively. At the microwave power level of 300 W, the torrefied rice straw and pennisetum both had the highest HHV's (20.97 and 26.51 MJ/kg), which were about 30 and 56% higher than those of as received rice straw and pennisetum, respectively. Generally, higher microwave power level contributed to higher heating value of torrefied biomass. However, when the microwave power level increased from 300 to 350 W, the HHV's of torrefied rice straw and pennisetum both decreased. This may imply that when the reaction temperature is over 400 °C due to higher microwave power levels (referring to Fig. 1), apparent part of the fixed carbon content of biomass can be reduced resulting in the decrease of heating value of torrefied biomass.

Table 2
Proximate and ultimate analyses of torrefied rice straw and pennisetum.

Reaction condition	Moisture (wt.%)	Proximate analysis (wt.%) [a]			Ultimate analysis (wt.%) [c]			
		Volatiles	Fixed carbon [b]	Ash	C	H	N	O [b]
Rice straw								
As received	5.46	88.75	1.43	9.82	46.24	6.21	1.32	46.23
150 W, 10 min	3.13	83.87	1.81	14.32	59.94	5.25	1.85	32.96
150 W, 25 min	2.86	83.12	1.51	15.37	56.52	5.77	2.01	35.70
200 W, 25 min	2.01	75.48	2.40	22.12	69.66	4.11	2.31	23.92
250 W, 25 min	2.52	69.24	2.98	27.78	76.65	2.76	2.12	18.48
300 W, 25 min	4.58	69.82	2.86	27.32	75.16	3.70	2.45	18.70
350 W, 25 min	1.41	69.16	3.14	27.69	78.83	2.92	2.16	16.08
Pennisetum								
As received	5.20	93.34	0.67	5.99	46.53	6.36	0.25	46.87
150 W, 10 min	1.21	93.27	1.37	5.37	54.10	5.73	0.30	39.87
150 W, 25 min	1.63	88.68	1.55	9.76	58.94	5.21	0.32	35.53
200 W, 25 min	1.27	84.41	2.18	13.41	69.10	4.62	0.35	25.93
250 W, 25 min	2.57	82.32	2.64	15.04	83.13	3.32	0.37	13.18
300 W, 25 min	1.13	81.39	2.89	15.72	82.71	2.96	0.28	14.05
350 W, 25 min	3.39	76.93	2.85	20.22	81.66	3.12	0.44	14.78

[a] Dry basis.
[b] Calculated by difference.
[c] Dry ash free basis.

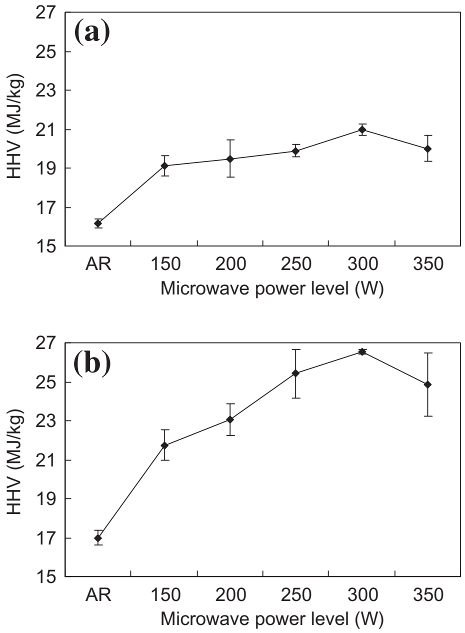

Fig. 2. Heating values of torrefied biomass at different microwave power levels for 25 min processing time (AR: as received). (a) Rice straw; (b) pennisetum.

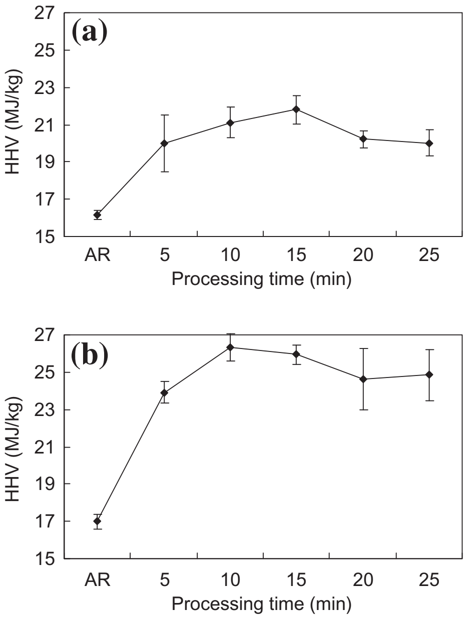

Fig. 3. Heating values of torrefied biomass at 350 W microwave power level for different processing time (AR: as received). (a) Rice straw; (b) pennisetum.

Since the 25 min processing time seems too long for biomass torrefaction at the microwave power level of 350 W, less processing time may be more suitable in the viewpoint of heating value. The heating values of torrefied biomass at the microwave power level of 350 W for different processing time are shown in Fig. 3. The highest HHV's of torrefied char were 21.80 and 26.33 MJ/kg for the processing time of 15 and 10 min and were about 35 and 55% higher than those of as received rice straw and pennisetum, respectively. Therefore, higher microwave power level contributed to less processing time because the required temperature (for the highest HHV) was reached earlier. From Figs. 2 and 3, it can be seen that the HHV's of torrefied pennisetum were about 14–28% higher than those of torrefied rice straw under the same reaction conditions (i.e., microwave power level and processing time). Therefore, maybe microwave torrefaction of pennisetum is more efficient than rice straw in producing high heating value torrefied biomass.

3.4. Correlations of reaction temperature with weight loss and heating value

In addition to the heating value of torrefied biomass, the weight loss of biomass after torrefaction should be an important factor as well. Almeida et al. (2010) used weight loss as an indicator of the severity of the torrefaction conditions. Fig. 4 shows linear relationships of reaction temperature with weight loss and heating value at the microwave power level of 150 W. At the same reaction temperature, the weight loss of rice straw and pennisetum were similar with each other. Reaction temperatures of 100 and 250 °C provided weight loss of around 10 and 50%, respectively. Unlike the weight loss, the heating values of torrefied rice straw and pennisetum were different at nearby reaction temperatures. The heating value increments of torrefied pennisetum were apparently larger than those of torrefied rice straw. At 250 °C reaction temperature, the heating

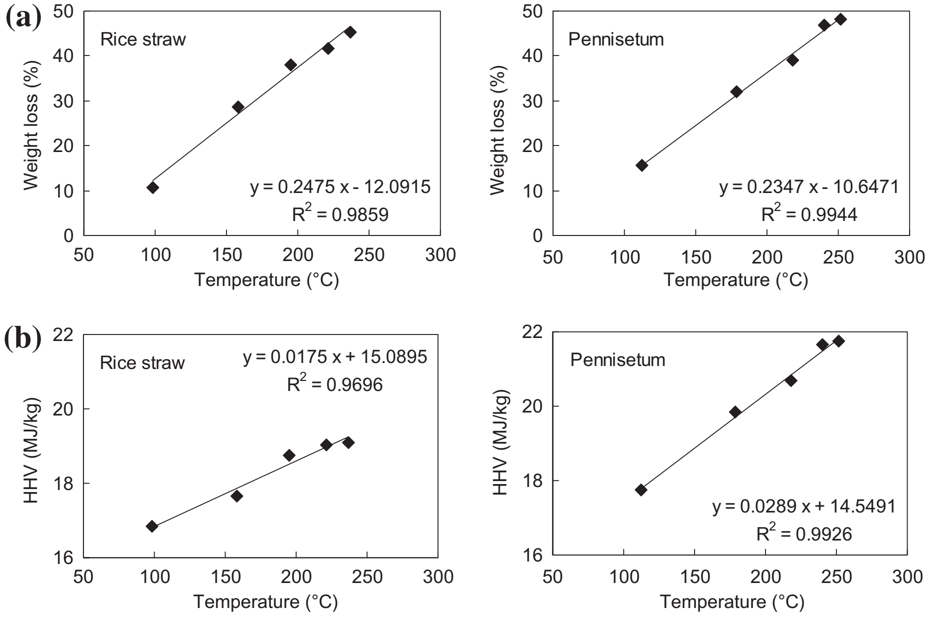

Fig. 4. Correlations of reaction temperature with (a) weight loss and (b) heating value at 150 W microwave power level.

values of torrefied rice straw and pennisetum were about 19 and 22 MJ/kg, respectively. Therefore, from the viewpoint of bioenergy preserved, maybe pennisetum is more suitable than rice straw for microwave torrefaction.

3.5. Kinetic analysis

The reaction kinetics of thermal decomposition of biomass by conventional (electrothermal) methods has been researched in much of the literature, but the kinetic analyses regarding microwave heating were very few. In this study, the kinetics of microwave torrefaction of rice straw and pennisetum at 150 W microwave power levels was analyzed. Reactions at higher microwave power levels were difficult to be analyzed due to their severe reactivity.

The rate equation for the kinetics analysis can be expressed as:

$$\frac{d\alpha}{dt} = A \cdot \exp\left(-\frac{E_a}{RT}\right) \cdot (1-\alpha)^n \quad (1)$$

where A is pre-exponential factor, E_a is activation energy, R is universal gas constant, n is the order of reaction, t is time, T is temperature, and α is conversion ratio of biomass:

$$\alpha = \frac{m_0 - m_t}{m_0 - m_f} \quad (2)$$

where m_0 is the initial mass of biomass sample, m_t is the mass at any time, and m_f is the final mass at the end of reaction. Under a constant heating rate $\beta (= dT/dt)$, Eq. (1) can be rearranged to:

$$\frac{d\alpha}{dT} = \frac{A}{\beta} \cdot \exp\left(-\frac{E_a}{RT}\right) \cdot (1-\alpha)^n \quad (3)$$

After a rearrangement and taking logarithms, Eq. (3) can be:

$$\ln\left[\frac{(d\alpha/dT)}{(1-\alpha)^n}\right] = \ln\left(\frac{A}{\beta}\right) - \frac{E_a}{RT} \quad (4)$$

A plot of $\ln[(d\alpha/dT)/(1-\alpha)^n]$ versus $1/T$ will yield a straight line fit of the data from which the decomposition order n can be selected (Chang, 1994). This can be seen as a differential method. Besides, by the Coats–Redfern integral method (Coats and Redfern, 1964), Eq. (3) can be integrated and rearranged to:

$$\ln\left[\frac{-\ln(1-\alpha)}{T^2}\right] = \ln\left[\frac{AR}{\beta E_a}\left(1 - \frac{2RT}{E_a}\right)\right] - \frac{E_a}{RT} (n = 1) \quad (5)$$

$$\ln\left[\frac{1-(1-\alpha)^{1-n}}{T^2(1-n)}\right] = \ln\left[\frac{AR}{\beta E_a}\left(1 - \frac{2RT}{E_a}\right)\right] - \frac{E_a}{RT} (n \neq 1) \quad (6)$$

From the linear regression of the left-hand-side term of the two equations versus $1/T$, the activation energy and the pre-exponential factor can be determined.

The first-, second-, and third-order kinetic parameters for microwave torrefaction at 150 W microwave power levels are shown in Table 3. The coefficients of determination (R^2) of linear regressions from the integral method were all over 0.99, while those from the differential method were only 0.94–098. The kinetic parameters calculated by the integral and differential methods were most close to each other when n was 2, especially for pennisetum. Therefore, by regarding the microwave torrefaction of pennisetum as a second-order reaction, the pre-exponential factors and activation energy would be about 0.04 1/s and 14 kJ/mol, respectively. The two parameters were very different from those for the thermal decomposition of single hemicellulose, cellulose, or lignin as reported before (Huang et al., 2011). This may be due to some factors such as heating manner, heating rate, and reaction mechanism.

Table 3
Kinetic parameters for microwave torrefaction of rice straw and pennisetum at 150 W microwave power levels.

Biomass	Method	n	A (1/s)	E_a (kJ/mol)	R^2
Rice straw	Integral	1	0.0169	11.11	0.9908
		2	0.0412	14.13	0.9979
		3	0.1297	17.48	0.9987
	Differential	1	0.0036	7.92	0.9421
		2	0.0176	12.30	0.9813
		3	0.0866	16.68	0.9845
Pennisetum	Integral	1	0.0161	10.47	0.9953
		2	0.0359	13.72	0.9973
		3	0.1175	17.37	0.9941
	Differential	1	0.0071	8.93	0.9363
		2	0.0362	13.48	0.9572
		3	0.1850	18.03	0.9592

3.6. Mass and energy yields

Bergman et al. (2005) have pointed out that both mass and energy yields are main parameters in the evaluation of torrefaction process and they describe the transition of mass and energy from the original to the torrefied biomass. The definitions of mass and energy yields can be found elsewhere (Wang et al. 2012). Table 4 shows the mass and energy yields of torrefied rice straw and pennisetum. Generally, higher microwave power levels led to lower mass and energy yields. When the processing time was controlled at 25 min, lower microwave power levels provided higher mass and energy yields and higher microwave power levels resulted in lower ones. At 150–200 W microwave power levels, the mass and energy yields were about 52 and 62% for rice straw, and 51 and 68% for pennisetum, respectively. At the microwave power levels as high as 250–350 W, the mass and energy yields were only about 35 and 44% for rice straw, and 27 and 41% for pennisetum, respectively. The low mass and energy yields are not surprising because of the high reaction temperatures (>300 °C) at the high microwave power levels. It is reasonable that more microwave irradiations should be able to provide higher weight loss, which might come from the drying, volatilization, and decomposition of biomass feedstock. Therefore, both mass and energy yields were lower due to more parts of the biomass were reacted at higher microwave power levels, even though the heating value of torrefied biomass was higher.

During the microwave torrefaction at 150 W microwave power levels, the rice straw and pennisetum both had the highest mass and energy yields when the processing time was 5 min. However, the very high mass yield (about 90%) showed that there was only a very small part of the hemicellulose content decomposed. In fact, the HHV's of rice straw and pennisetum torrefied for 5 min were only 16.84 and 17.74 MJ/kg, respectively, which were slightly higher than those of as-received biomass feedstocks. The heating value of hemicellulose (13.6 MJ/kg) is just about half that of lignin (27 MJ/kg) (van Heiningen, 2006). Therefore, the decomposition of hemicellulose content should be very helpful in raising the heating value of torrefied biomass. After the processing time of 10 min, the mass and energy yields were 71.40 and 78.02% for rice straw, and 68.09 and 79.56% for pennisetum, respectively. The about 70% mass yield means that, by referring to Table 1, the moisture, extractives, and hemicellulose contents of biomass feedstocks were nearly all vaporized, volatilized, decomposed, or carbonized, so further thermal treatment might be unnecessary.

3.7. Mass and energy balance

In addition to torrefied biomass, liquid and gaseous products were also collected and analyzed, as shown in Tables S1–S3 in the Supplementary data. Therefore, mass and energy balance before and after microwave torrefaction can be calculated, as shown in Fig. 5. After the microwave torrefaction at 150 W microwave power levels for 10 min processing time, 1 mass unit (M) and 1 energy unit (E) of raw rice straw was converted into 0.72 M and 0.78 E of solid, 0.21 M and 0.19 E of liquid, and 0.07 M and 0.03 E of gas. Besides, 1 M and 1 E of raw pennisetum was converted into 0.68 M and 0.80 E of solid, 0.24 M and 0.15 E of liquid, and 0.08 M and 0.05 E of gas. Generally, for both biomass feedstocks, about 70% mass and 80% energy retained in torrefied biomass, and about 30% mass and 20% energy shifted to liquid and gaseous products. Therefore, the energy density of torrefied biomass can be about 14% higher than that of raw biomass. The byproducts of microwave torrefaction, condensable liquid and incondensable gas, can be used as energy sources for pretreatment of biomass or other purposes.

Table 4
Mass and energy yields of torrefied rice straw and pennisetum.

Power (W)	Time (min)	Mass yield (%)		Energy yield (%)	
		Rice straw	Pennisetum	Rice straw	Pennisetum
150	5	89.23	84.38	92.98	88.15
150	10	71.40	68.09	78.02	79.56
150	15	61.85	60.99	71.74	74.26
150	20	58.37	53.14	68.69	67.73
150	25	54.65	51.70	64.62	66.17
200	25	49.10	50.92	59.22	69.12
250	25	34.87	28.25	42.90	42.29
300	25	34.16	26.95	44.34	42.07
350	25	35.12	25.58	43.48	37.42

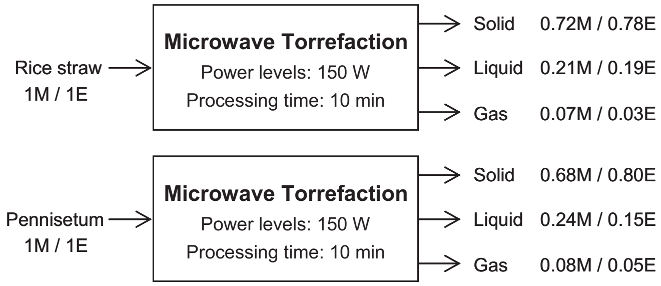

Fig. 5. Mass and energy balance of microwave torrefaction of rice straw and pennisetum (M: mass unit; E: energy unit).

3.8. Applications of microwave torrefaction

This article studied the microwave torrefaction of often seen and easily obtained agricultural residue, the rice straw, and forage grass, the pennisetum. The good performance above-mentioned shows that microwave torrefaction should be feasible for wide biomass sources. Compared with conventional methods, the processing time of microwave torrefaction can be less to reach the expected mass and energy yields, and only low microwave power levels are necessary. Therefore, the energy input (electricity) of microwave torrefaction can be relatively less. The torrefaction byproducts (liquid and gas) can be utilized to generate heat or electricity, so the overall energy efficiency of microwave torrefaction can be further promoted. Besides, with proper refinery and manufacture processes, the byproducts could be regarded as the resources of green chemicals. The ultimate goal of biomass torrefaction should be to employ the least energy to acquire the torrefied biomass retaining the most bioenergy. According to this study, the microwave torrefaction of biomass should be a competitive and applicable technology.

4. Conclusions

The heating rates and reaction temperatures of microwave torrefaction were higher at higher microwave power levels. Only 150 W microwave power levels and 10 min processing time were needed to meet about 70% mass yield and 80% energy yield, so the energy density of torrefied biomass was 14% higher than that of raw biomass. Liquid and gaseous products possessed about 30% mass and 20% energy of raw biomass. First-order kinetic parameters were determined with good coefficients of determination. Microwave torrefaction of biomass could be a competitive technology to produce torrefied biomass retaining the most bioenergy with the highest energy efficiency.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2012.08.006.

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